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SUMMARY PAGE

THE PROBLEM

When the direction of the gravitoinertial vertical is changed relative to a man riding on a centrifuge, there is a lag in his perception of this change. Previous workers have distinguished two components of the perceptual lag, a visual and a nonvisual one. The present experiment was undertaken to test the hypothesis that the nonvisual component can be attributed largely to discordance between information received from the semicircular canals and from the otolith organs.

FINDINGS

A device was used to tilt seated subjects laterally 30 deg relative to gravity. Under these circumstances, information about angular velocity received from the semicircular canals is consistent with information about the axis of reorientation received from the otolith and somatosensory systems. Immediately after tilt, estimates of verticality were approximately accurate and there was no significant shift in subsequent estimates made throughout a 140-sec judgment period. The absence of a perceptual lag in the present situation supports the hypothesis. An understanding of the factors which control the presence or absence of perceptual lags of this kind is essential to the prediction of perceived attitude in almost every aircraft maneuver involving a change in the state of motion during conditions of poor visibility.

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INTRODUCTION

In flight, as in natural movement, the semicircular canals and otolith structures are usually stimulated simultaneously. Typically these receptors have been studied in the laboratory as if they were independent systems, but the importance of considering interactions between them has been indicated in the past (9, 13) and has been re-emphasized by recent evidence. Several studies suggest that semicircular canal responses exert an influence on the dynamic perception of "the vertical" (2,5,6). In those experiments, the subject was positioned so that his z-axis was Earth-horizontal, and then he was rotated about that axis. This type of rotation produced continuous reorientation of the otolith organs with respect to gravity. At 30 rpm, subjects were approximately correct in signaling orientation relative to gravity for a period of 30 to 50 sec, that is, during the period of time required for the cupula response to subside; thereafter, they were unable to signal their orientation correctly (2). When the speed of rotation was reduced to 10 rpm, most subjects perceived their orientation throughout the period of rotation. From these results, Guedry (6) concluded that during a rapid change in the direction of a linear acceleration vector, the direction of the vector is not perceived accurately when otolith information is not supplemented by appropriate information from the semicircular canals.

A similar interpretation was applied to results from a quite different experimental situation in which subjects were exposed to linear oscillation on a parallel swing (7, 12) and on a horizontal track (10). When subjects were firmly restrained during oscillation on either of these devices, they were subjected to no angular acceleration; therefore, canal stimulation was nil (according to classical concepts), whereas the resultant linear acceleration vector oscillated back and forth through angular displacements as large as 30 deg. Subjects in this situation felt only slightly tilted (12) or experienced no tilt at all (7, 10), implying again that, when supplementary canal information is lacking, perception of tilt is minimized.

Guedry (6) suggested that a similar process may be in part responsible for the lag in the perception of gravitoinertial vertical (cf. 1,4) because, when a subject is seated upright at a distance from the center of rotation on a centrifuge, the initial angular acceleration causes semicircular canals to signal rotation in a plane that is perpendicular to the one in which the gravitoinertial force changes direction. Thus, in this case, the canals not only fail to provide supplementary information regarding the axis of tilt, but they produce signals that conflict with those coming from the otolith organs. The lag in perception of the gravitoinertial vertical on the centrifuge must be largely the result of the manner in which the subject is tilted and probably is due to discordance between canal and otolith information during the initial period of tilt.

If, instead, a subject were to be tilted in the normal manner, that is, simply tilted with respect to gravity about an Earth-horizontal axis with an acceleration profile to permit supplementary canal information regarding angular displacement (cf. 11), then perception of bodily orientation should be both immediate and veridical. The present experiment was undertaken to test this prediction.

PROCEDURE

SUBJECTS

Eighteen young men with no apparent vestibular defects served as subjects for this experiment. Nine of the subjects were laboratory personnel who had previous experience on the device; the remaining were student aviators.

APPARATUS

The rotary device used in this experiment has been described previously (5). Briefly, the device, as used in this experiment, allowed the subject to be tilted in the y-z (frontal) plane* either clockwise or counterclockwise to a predetermined tilt position (ϕ_x) with independently variable acceleration (6 deg/sec^2 maximum) and velocity (18 deg/sec maximum). The experimenter was able to monitor continuously the inclination of the subject within 0.5 deg. Subjects were firmly secured by means of safety straps across the head, chest, thighs, and feet to a metal chair mounted on the tilt device.

An illuminated column of light, 1 mm by 10 cm, was mounted in front of the subject at a distance of 1 m. The lighted column could be rotated either clockwise or counterclockwise in the subject's y-z plane by the experimenter or by the subject (by the latter with hand-held pushbuttons). The experimenter could read the inclination of the lighted column to the nearest 0.1 deg. The control and readout mechanism for the lighted column has been described by Correia, Hixson, and Niven (3).

The entire apparatus was draped with opaque material to exclude all extraneous light.

METHOD

The tilt angle, ϕ_x, used in this experiment was 30 deg. One group of six subjects was tilted at a rate well above the threshold for canal stimulation. The angular acceleration, α_x, for these subjects was 6 deg/sec^2, followed by a 6 deg/sec^2 deceleration. The other group of six subjects was tilted slowly at a constant velocity of 1 deg/sec. The small angular impulses involved in starting and stopping rotation at 1 deg/sec are near absolute threshold for canal stimulation, so this group did not receive canal information which by itself would permit accurate perception of angular displacement (cf. 11).

The accuracy of estimates made by these two groups of subjects suggested the possibility that somesthetic cues were a more important factor in the present experiment

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*The nomenclature system proposed by Hixson, Niven, and Correia (8) is used here.

than in the situation used by Clark and Graybiel (1). Since it was desired to compare the present results with those of Clark and Graybiel, the entire experiment was repeated with the chair well padded and the subjects wearing an orthopedic neck brace to minimize head movements. Six subjects were tilted quickly and six subjects were tilted slowly under this condition. Some of these subjects were the same ones used previously.

The experimental procedure, the same for all subjects regardless of the group to which they were assigned, was as follows: The subject was secured in the chair and positioned so that his z-axis was aligned with gravity. He was instructed to keep his eyes closed at all times except when making a judgment. Then the experimenter offset the lighted column and instructed the subject to align it with Earth-vertical. This procedure was repeated three more times. The mean of these four judgments was defined as the "visual vertical" and was used as a reference in calculating accuracy of all subsequent judgments. The subject was then tilted 30 deg to his left side and immediately instructed to align the lighted column with Earth-vertical. When he completed his judgment, he signaled the experimenter and closed his eyes; whereupon the experimenter offset the line for the next trial. (Magnitude and direction of the offset occurred in a quasirandom sequence.) This procedure was repeated at 20-sec intervals until the subject had made eight judgments. Then he was rotated until he achieved a 30-deg tilt to his right side and the procedure was repeated. In total, each subject made eight judgments at each of six successive 30-deg tilts, three to his left side and three to his right, in alternating sequence.

RESULTS AND DISCUSSION

Under all conditions of the experiment, subjects were able to accurately estimate the visual vertical immediately upon being tilted and continued to make accurate estimates throughout the judgment period. Subjects who received 6 deg/sec^2 angular acceleration while being tilted (Figure 1) appeared to show an Aubert effect, whereas subjects tilted at 1 deg/sec^2 (Figure 2) displayed a slight Müller effect. The difference between judgments made under these two conditions was significant at $\underline{p} = .05$ but did not reach significance at $\underline{p} = .01$. Thus it appears that the faster tilt caused subjects to displace visual vertical farther from their own z-axis, but this effect was a weak one, amounting to an average of about 3.7 deg.

For subjects who received a 6 deg/sec^2 angular acceleration while being tilted, stimulation of the semicircular canals provided information about the axis of tilt that supplemented information received from the otolith organs. Visual vertical estimates by these subjects can be compared in Figure 1 with estimates of the visual vertical made by subjects who rapidly underwent a 30-deg change in the direction of the gravitoinertial force on a centrifuge (1). The latter subjects displayed the familiar lag effect.

Figure 2 shows the estimates of groups which were tilted at a rate near the threshold of canal stimulation. It appears from these data that the lack of adequate

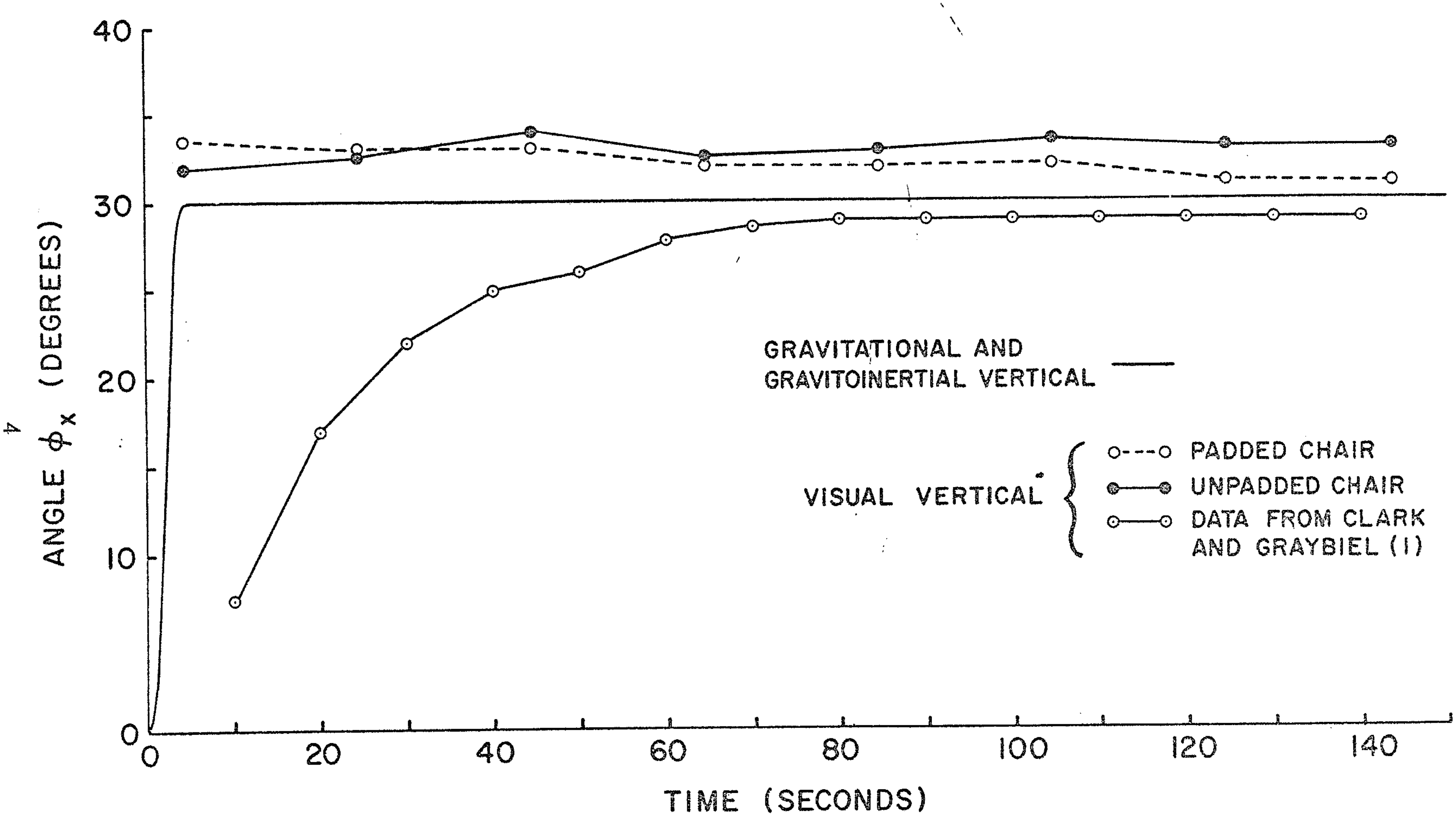

Figure 1

Mean estimates of visual vertical for subjects tilted at the rate of 6 deg/sec^2. Data were combined for both right and left directions of tilt. On the ordinate, angular displacements are expressed in degrees from the subject's z-axis. The solid line represents approximate angular displacement from the subject's z-axis of the gravitational vertical in the present experiment and of the gravitoinertial vertical in Clark and Graybiel (1). Plotted circles (open, closed, or dotted) represent angular displacement from the subject's z-axis of the lighted column used to indicate the visual vertical.

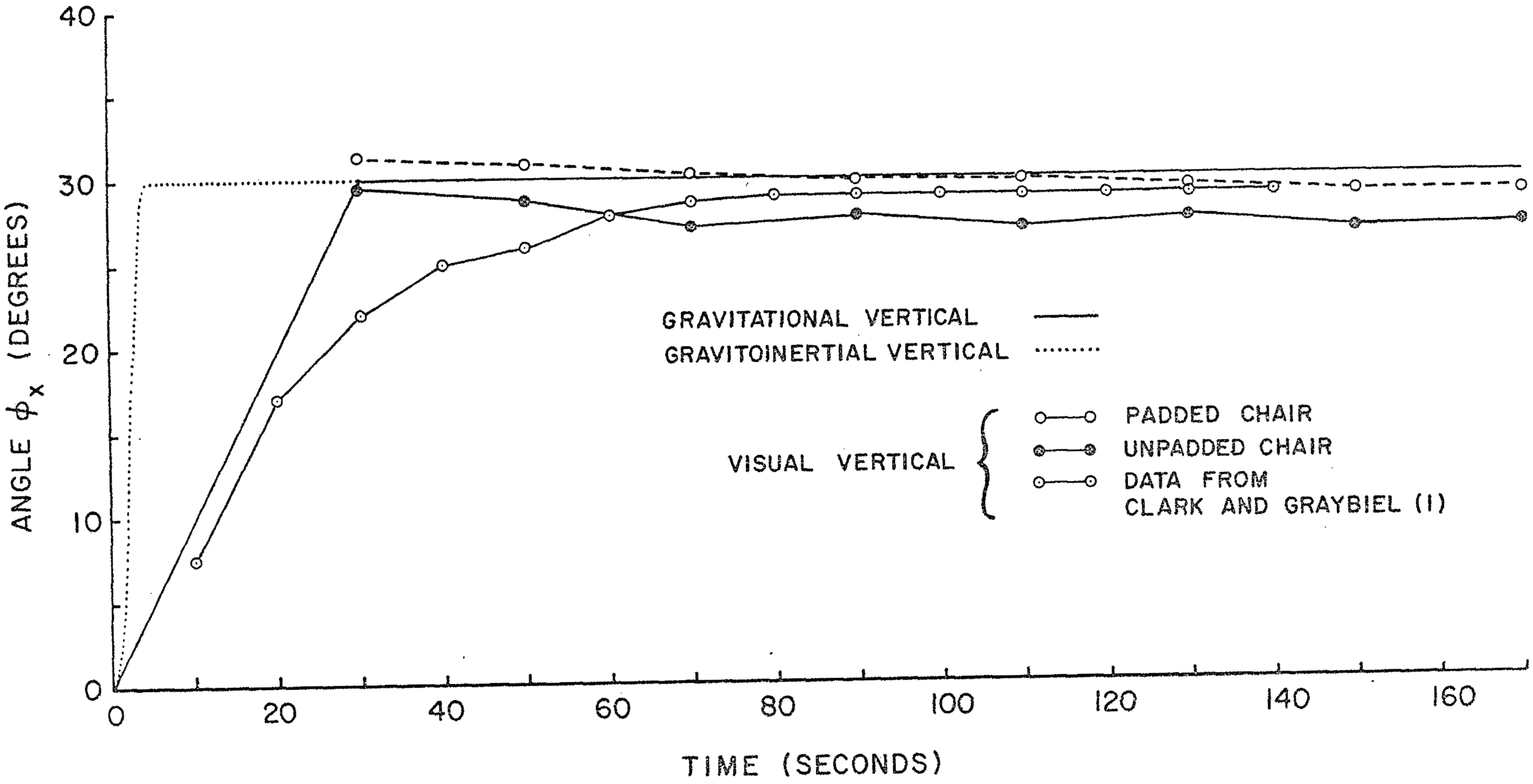

Figure 2

Mean estimates of visual vertical for subjects tilted at a rate of 1 deg/sec. Data were combined for both right and left directions of tilt. On the ordinate, angular displacements are expressed in degrees from the subject's z-axis. The solid line represents approximate angular displacement of gravitational vertical from the subject's z-axis in the present experiment. The dotted line represents approximate angular displacement of gravitoinertial vertical from subject's z-axis in Clark and Graybiel (1). Plotted circles (open, closed, or dotted) represent angular displacement from subject's z-axis of the lighted column used to indicate the visual vertical.

canal information does not in itself impair the accuracy of estimating verticality. However, in this case the tilt was accomplished very slowly; over 30 sec were required to achieve the full 30-deg tilt. In previous studies when subjects were oscillated on a parallel swing (7, 12) or on a horizontal track (10), the resultant linear force changed direction relative to the body more quickly and little or no tilt was perceived. In other words, in the absence of supplementary canal information, the more rapid tilts were not perceived. Thus it appears that subjects are able to accurately estimate visual vertical soon after being tilted without supplementary canal information, but only when the tilt is sufficiently slow.

A comparison is made in Figure 2 between estimates of visual vertical following slow tilt in the present study and those made by subjects tilted relative to the gravitoinertial vertical on a centrifuge (1). It can be seen that, whereas subjects in the present study made accurate estimates of visual vertical immediately after achieving full tilt, subjects on the centrifuge made estimates that amounted to only about 80 per cent of the true change in gravitoinertial vertical after 30 sec of constant rotation. This difference, while it is not a large one, may indicate that discordant canal information retards the accurate perception of the vertical more than does the absence of a canal input.

Graybiel and his associates have thoroughly investigated the perception of gravitoinertial vertical; they succeeded in separating two interacting components of the effect, a visual and a nonvisual one. Clark and Graybiel (1) suggested that the interaction of the visual and nonvisual factors is responsible for the lag in perception of gravitoinertial vertical. To explain the nature of the interaction, they used Helson's concept of "cross modality interaction," according to which incoming information from the various sense organs is weighted to form immediate percepts. They assumed that visual factors, which inform the subject that he is aligned with gravity, receive less weight as rotation continues, while nonvisual factors, telling him that he is tilted, receive increasingly greater weight. The shift in weighting between these two factors is presumed to lag behind the change in direction of the resultant force, so a lag appears in perception of the gravitoinertial vertical.

The results of the present study complement those of Clark and Graybiel by suggesting a reason why the nonvisual factor should receive increased weight during constant velocity rotation. At the beginning of rotation, semicircular canals produce discordant information which impairs perception of the direction of the gravitoinertial force. The canals signal rotation about the subject's z-axis, whereas the change in direction of the gravitoinertial force implies rotation primarily about the subject's x-axis. After constant velocity is reached, canal response slowly subsides, the conflict diminishes, and veridical perception is attained.

Support for this interpretation comes from the striking similarity between the rise in the nonvisual component and the decay of semicircular canal stimulation, as shown in Figure 3. The solid line represents the nonvisual component of the perception of gravitoinertial vertical, described by Clark and Graybiel (1). The dotted line represents

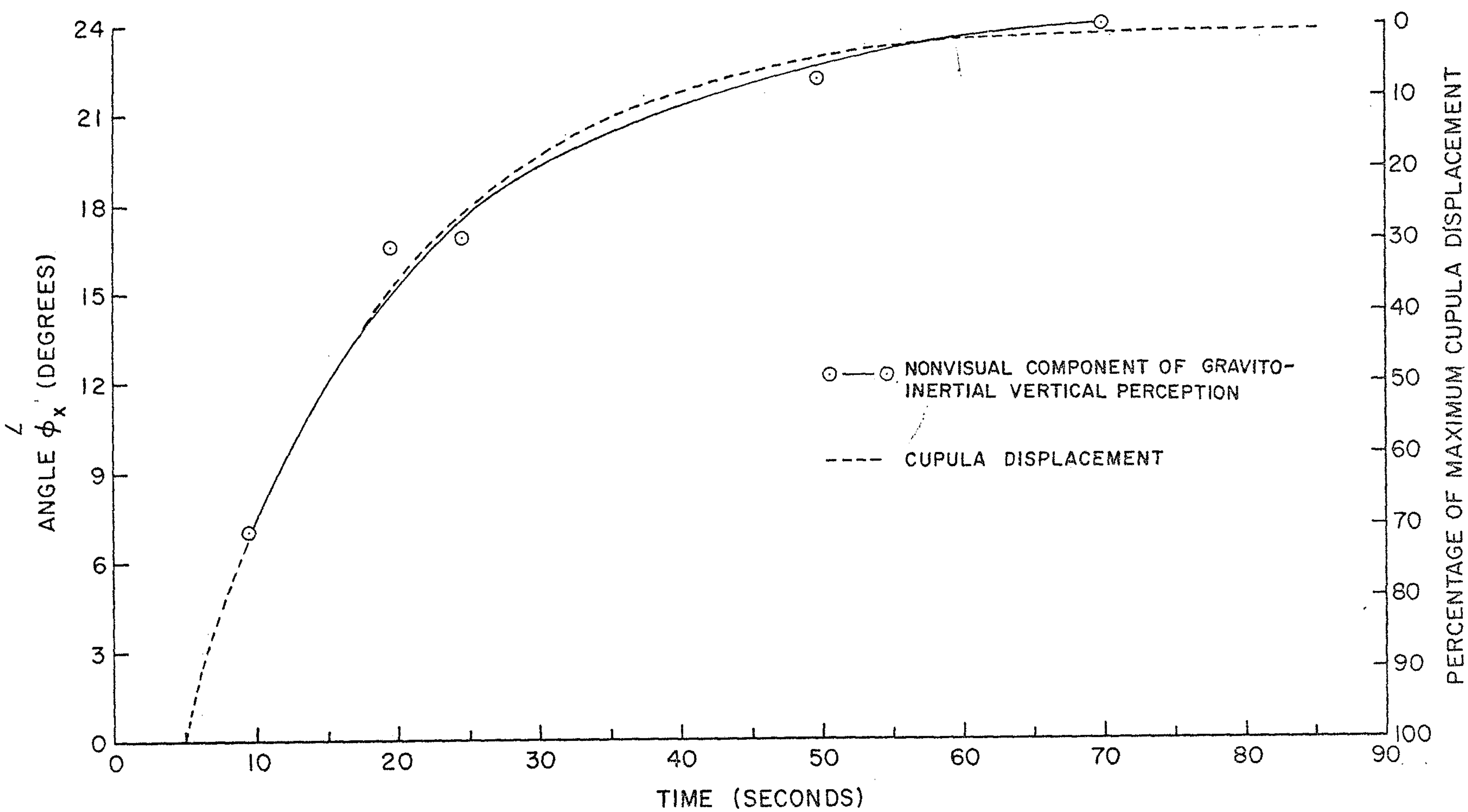

Figure 3

Comparison of theoretical values of cupula displacement with the nonvisual component of gravitoinertial vertical perception reported by Clark and Graybiel (1). Cupula displacement derived according to van Egmond (14) assuming a time constant of 15 sec.

the theoretical function for cupula return following an angular acceleration, assuming a time constant of 15 sec (14). The close relationship shown here is what one would expect if discordant canal signals contribute to the lag in perception of the gravito-inertial vertical on the centrifuge.

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13. ABSTRACT

When a man is accelerated on a centrifuge, the direction of gravitoinertial vertical changes relative to his body. However, a lag occurs in his perception of this change. The hypothesis has been advanced that the perceptual lag in this situation is partly the result of a conflict between signals arising from the semicircular canals and from the otolith organs. To test this hypothesis, subjects were tilted in such a way that they received consistent semicircular canal and otolith signals. This was accomplished simply by tilting them 30 deg from upright in their frontal plane. Immediately after being tilted, these subjects made estimates of the vertical which were approximately accurate, and they continued to make accurate estimates throughout a 140-sec judgment period. The absence of a perceptual lag under these circumstances supports the hypothesis.

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